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Environmental performance optimization of window–wall ratio for different window type in hot summer and cold winter zone in China based on life cycle assessment

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ABSTRACT

This study aims at analyzing the environmental impact of each process of a typical office building over its entire life cycle in Shanghai, China, and finding out a suited limited value for window–wall ratio (WWR) of different orientation and window materials by comparing the results of different scenarios. Life cycle assessment (LCA) is used as a tool for the assessment of energy consumption and associated impacts generated from utilization of energy in building construction and operation.

When looking at the impacts due to building external envelope production, we observed a small but significant environmental benefit as WWR increasing. Depending on the window materials, the impact is reduced by 9–15%. The environmental benefit associated with the changing in building external envelope production mainly results from the high coefficient of recovery of window materials, include window-frame and glass. But for building use phase, WWR with different window types or orientation has various effects on environmental burden. The environmental impact of office buildings is dominated by the operation stage, although the environmental burden of material production for low-E hollow glass window is larger than single glazing window, the environmental performance of building with low-E hollow glass window is better than other window materials.

1. Introduction

The window to wall area ratio (WWR) has an important effect on building energy consumption for heating and air conditioning. For one thing, solar heat gains will be increased as the WWR ratio increasing, on the other hand, the heat exchange will be also increased for the heat transfer coefficient of window is usually larger than wall. WWR of office building is limited strictly according to the design standard for energy-efficiency of buildings in hot summer and cold winter zone in China, for it is the dominant influencing factor of the air conditioning and heating energy consumption in building use phase.

Most papers published so far in the engineering domain have focused on the impact of WWR on the heating and air conditioning energy consumption in residential buildings, few studies discussed the relationship between WWR and life cycle environmental load in office buildings. Influence of WWR on annual energy consumption of heating and air conditioning system of residential buildings in hot summer and cold winter region under different orientation has been performed [1–3]. However, the energy consumption of materials production, materials and energy transportation, materials reusing varies while WWR changing and environmental emissions of different life cycle stage should be further incorporated. From the life cycle point of view, all life cycle phases should be studied to understand the total energy consumption and environmental emissions of building under different WWR. The study refers to a typical office building in Shanghai, China. The aim is to quantify the difference between the life cycle environmental performance of different hypothetic scenarios for WWR value varies from 0.1 to 0.7 of each window orientation and each window material, and to find out a suited limited value for WWR of different window materials of a typical office building.

2. Materials and methods

The LCA was performed according to the ISO standards on LCA and to the main steps described in ISO norm 14041.

The inventory analysis is the most important stage in the process of LCA. Energy, greenhouse gases and principal pollution emissions are covered in the life cycle inventory (LCI) models of building energy system, which are the so-called environmental load factors. These life cycle factors are the integrations of direct environmental load on the use phase of building, and indirect environmental load on the phase of energy recovery, energy

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production, transportation, and building materials production. BIN method is used to calculate the building energy consumption of building use phase [4], then the environmental emissions based on the direct and indirect load of building materials, and the indirect load of raw and processed materials as well. This model can be used to study the LCI of various building raw materials. The correlation between different energy resources in the life cycle of building is very complex. Special software is then needed in building LCA. The energy consumption of heating and air-conditioning is developed at Microsoft Excel® spreadsheets and added to BESLCI program developed by Huang [5] to be utilized in this paper.

2.1. Functional unit and system boundaries

The function of office building is to provide work space for people. The functional unit chosen to represent the system was defined as 1 m^2 of building area.

2.2. System boundary

Compared to common products, building is a integrated system due to its long life-span and complicated composing. The LCA process of building has three major stages, building materials production phase, building operation phase, and end-of-life phase. Each phase includes producing, transportation, distributing and so on. Heating and air conditioning are considered in building operation phase. On contrary to building envelope, building frame has no impact on energy consumption of building operation stage, thus LCA of building can be divided into three components: building envelope, building frame and building use phase, each part can be assumed as a individual product, then the system boundary of building LCA can be described as in Fig. 1.

2.3. Description of the system under study

An office building in Shanghai, China is investigated in this study, and several schemes of window design are analyzed. The building has 21 floors with total building area 46240 m^2, the external envelope area of each building orientation (north, south, east and west) is 5000 m^2, and the designed life-span is 50 years.

The data obtained for the LCA are mainly from primary sources; secondary data, such as existing literature data; calculations and measurements are used in the absence of primary data.

The *U*-value (heat transfer coefficient) of wall made up of aerated concrete block is 0.89 $W/m^2 K$, and for roof it is 0.6 $W/m^2 K$. The window-frame constructed by aluminium alloys occupies 25% area of total window, of which the *U*-value is 6.21 $W/m^2 K$, three scenarios are considered regarding the glass type of window: single glazing window, hollow window and low-E hollow window. The *U*-value of each type window is described in Table 1.

Window of different orientation has different effects on solar heat gain due to different cooling load factors (CLFs), cooling load temperature differences (CLTDs) and maximum solar heat gain factors (MSHGFs), but there is scarcely any difference between west and east orientation, so three orientations (South, North, West/East) are taken into account in each case.

Energy, greenhouse gases and principal pollution emissions are covered in the life cycle inventory models of building energy system. Greenhouse gases are made up of CO_2, CH_4, N_2O and the CFC. Principal pollution emissions (O_3, CO, NO_x, PM10 and SOx) are divided into overall emissions and urban emissions due to the regional impacts of the pollution.

For the emissions of environmental burden are various, some types of pollution emissions in one senario may be large than those in other cases while other types of emissions are less. And the impacting of each emission to environment is different even if the quantity is same. So the impact assessment is needed to quantify the environmental burden of the building under each case.

The impact of emissions to environmental impacting is classified into energy exhaustion potential (mineral fuel exhaust), global warming potential (greenhouse gas emissions), atmosphere environment impact (total contamination emissions) and urban atmosphere environment impact (urban contamination emissions). The weight factor of each class is 0.25.

The energy exhaustion potential and global warming potential are characterized using the equivalent method [6]. The atmosphere environment impacting is characterized by the critical volume dilution method [7]. In this paper, the atmosphere environment impacting and urban atmosphere environment impacting are calculated based on the contamination emissions standard of three regions prescribed by Chinese Environmental Quality Standard.

Single glazing window with the WWR ratio 0.4 in each building orientation is taken as a base case in this paper. In the base case, the LCA results of all classifications are set to 1, so the total LCA result of base case is 4 according to the equivalent weight factor of four classes of environmental impact. And the value of other cases is a dimensionless index relative to the base case.

For each glass type, the building LCA results under the condition of WWR of one orientation varies from 0.1 to 0.7 while of other orientations is kept 0.4 are compared to the base case, so all the LCA results are dimensionless value. There are 63 different cases (3 types of window × 3 window orientations × 7 WWRs) in this study.

In the present study, the concrete is assumed to be one-off due to its significantly low recovery rate. The recovery rate of aluminium alloy and glass are very high, here the concept of

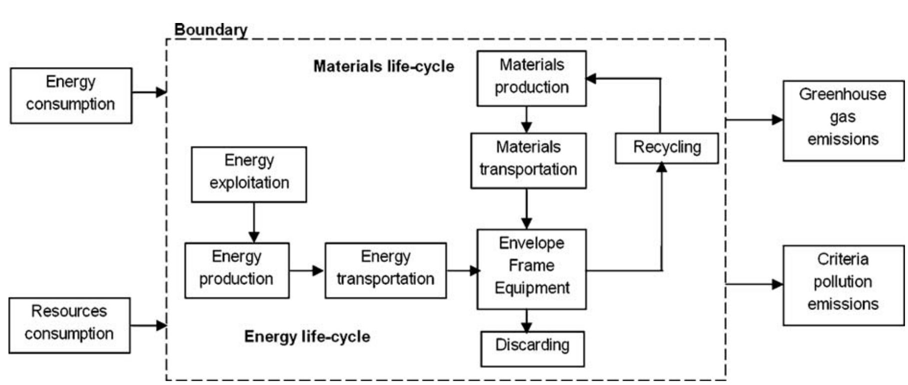

Fig. 1. Boundary of LCA in building energy system.

Table 1
Heat parameter of window.

Glass type	Heat transfer coefficient of glass ($W/m^2 K$)	Heat transfer coefficient of window ($W/m^2 K$)
Single glazing 3 mm	6.17	5.56
Hollow glass 3 + 12 + 3 mm	3.14	3.29
Low-E hollow glass 5 + 12 + 3 mm	1.88	2.34

integrated recovery rate indicated by the symbol of η is introduced

$$\eta = \alpha\beta \tag{1}$$

where α is recovery capacity of one material, β is whole recovery level of one material, it also means the proportion of the recycled material used to total used of this material. So the average energy consumption of material production in its life cycle can be calculated with Eq. (2)

$$\begin{aligned}\bar{A} &= \frac{A+(\beta B+\eta C)+\eta(\beta B+\eta C)+\eta^2(\beta B+\eta C)+\cdots+\eta^n(\beta B+\eta C)}{1+\eta+\eta^2+\cdots+\eta^n} \\ &= \frac{A+\beta B/1-\eta+\eta C/1-\eta}{1/1-\eta} = A(1-\eta)+\beta B+\eta C\end{aligned} \tag{2}$$

where $\bar{A}$ is the average energy consumption of material production in its own life cycle, A is the energy consumption of raw material mining, B is the energy consumption of material transportation, C is the energy consumption of material regeneration.

The recovery capacity of aluminium alloy and glass are 100% and 90% respectively, and the recovery level in China is 80% and 13% [8], so the integrated recovery rate of them are 80% and 11.7% separately. Then with the BESLCI software the total energy consumption of the aluminium alloy and glass in the building life cycle can be calculated, so as the life cycle environmental emissions.

3. Results and discussion

According to the systems defined by the functional unit, the results obtained are comparable in comparatively values. The WWR and window type have no influence on LCA results of building frame, therefore the LCA result of building frame of each case in this study is a fixed value. Below are the LCA results of external and building operation stage.

3.1. LCA results of external envelope

The life cycle energy consumption and environmental emissions of external envelope have no relationship to the orientation, because the external envelope area of each building orientation is equal to others in this study.

Fig. 2 presents the relationship between life cycle environmental impact results of external envelope and WWR, and Fig. 3 shows the normalized impact category values of external envelope taking low-E hollow glass window as an example. It is found that the life cycle energy consumption and environmental emissions of external envelope decrease linearly as the WWR increased, especially for the global warming potential. The environmental impact of building envelope with single glazing window decreases most quickly for it consumed less aluminium alloy than hollow glass and low-E hollow glass window in equal area.

3.2. LCA results of building use phase

To make it easy to compare the energy consumption and environmental emissions in building use phase among different

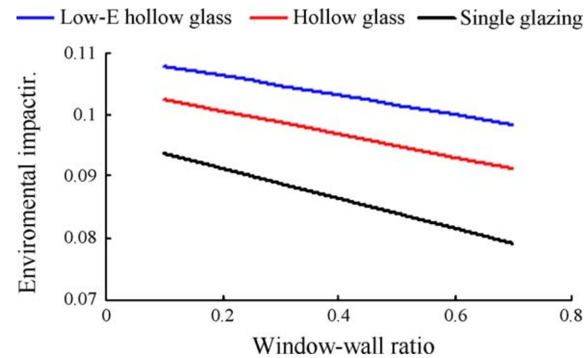

Fig. 2. The environmental impact of external envelope.

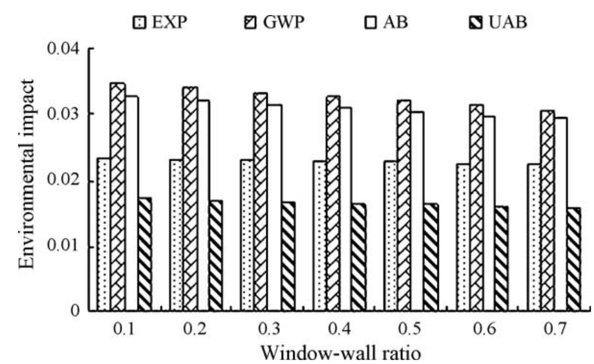

Fig. 3. The environmental impact of external envelope with low-E hollow glass window.

cases, the screw chiller and oil fuel boiler are assumed to be the sources of air conditioning and heating in each case, respectively. The equipments could be chosen based on the cooling and heating load under different frequency bands calculated by the BIN method. Multiple screw chillers may be chosen for some cases. When energy consumption of air conditioning in summer is calculated, not only the number of chiller is controlled in operation, but also the performance under partial load should be considered. And the pumps are supposed to be at constant-rate of flow, thus only the number is controlled in operation. As the method proposed by Ju [9], the relationship between screw chillers power and partial load rate is fitted. The power of chillers under each frequency can be calculated by the partial load rate, and therefore the summer energy consumption can be eventually obtained.

As for the heating source of boiler used in winter, the energy consumption can be calculated by the equivalent time of full load. The efficiency of oil fuel boiler is assumed to be 88% [10]. Limited by the space, calculation process is not given here. Fig. 4(a) and (b) show the effects of WWR of low-E hollow glass window on life cycle environmental impact of air conditioning and heating respectively.

From Fig. 4(a), it can be seen that environmental impact of air conditioning would be increased significantly with the WWR of any orientation increasing, especially east orientation. There are two reasons for this. First, solar radiation heat gain would be sharply increased when the window area increases. Second, the U-value of window is larger than wall, as the WWR increases, conduction heat gain through the exterior envelope will be also increased, the increasing amplitude is independent of exterior envelope orientation.

Fig. 4(b) shows that the environmental impact of heating is decreased with increasing of WWR of east or south orientation, and the WWR of north orientation has little effect on the environmental impact of heating.

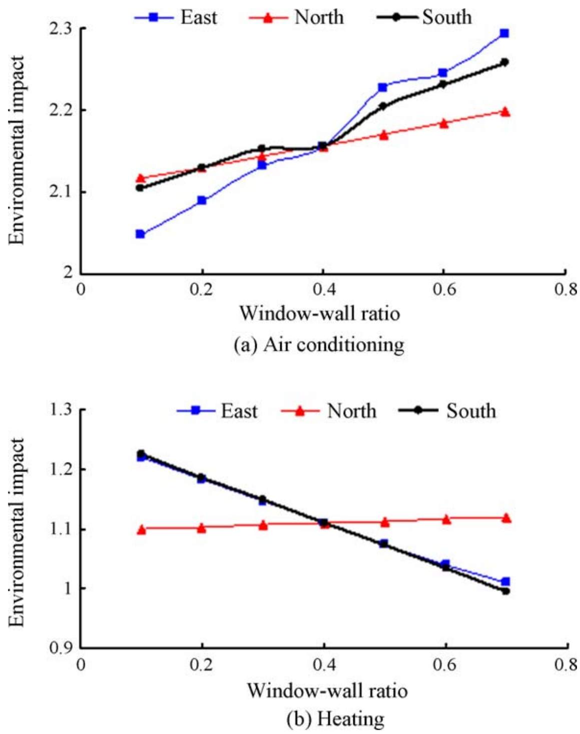

Fig. 4. The relationship between environmental impact of heating and air conditioning and WWR with the low-E hollow glass window.

Through comparison of y-axis values of Figs. 2–4, it can be concluded that the environmental impact of air conditioning shares the maximum proportion of the whole building life cycle, next comes heating, and building external envelope takes the lowest proportion (about 3%).

3.3. LCA results of whole building life cycle

Figs. 5–7 shows the effect of WWR of different orientation and window type on environmental impact of whole building life cycle. For single glazing window, the increasing of WWR of any orientation would make a markedly increasing of the life cycle environmental load, especially for north orientation of which the WWR should be as low as possible, and the WWR of east orientation has to be below 0.4, for south orientation the upper limit is recommend as 0.5. For hollow glass window, the WWR increasing of any orientation would induce a very slight increasing of environmental load. But for low-E hollow glass window, the WWR has little effect on life cycle environmental load of whole, even when the WWR of south orientation increases, there is a minor decreasing of environmental impact.

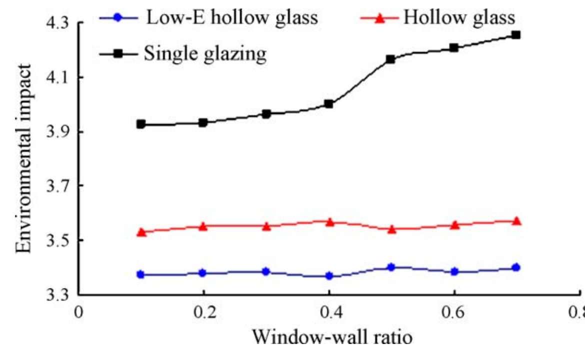

Fig. 5. Effect of east orientation WWR on the LCA result.

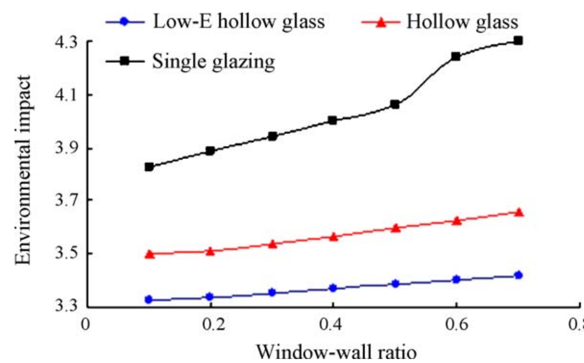

Fig. 6. Effect of north orientation WWR on the LCA result.

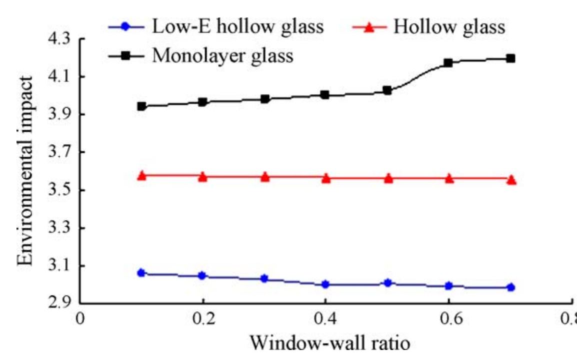

Fig. 7. Effect of south orientation WWR on the LCA result.

Table 2 shows the LCA results of whole building of all cases, the effect of WWR on life cycle environmental impact is most significant for single glazing window, especially for north orientation that the maximum difference among LCA results under different WWR can be up to 11%. For hollow glass window and low-E hollow glass window, the promotion potential of

Table 2
Environmental impact of different window type and WWR.

Orientation	Window type	WWR							Maximum relative difference (%)
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	
East	Low-E hollow glass	3.374	3.377	3.383	3.370	3.402	3.383	3.402	0.94
	Hollow glass	3.534	3.551	3.551	3.568	3.544	3.557	3.573	1.09
	Single glazing	3.927	3.931	3.964	4.000	4.165	4.208	4.254	7.68
North	Low-E hollow glass	3.325	3.340	3.355	3.370	3.386	3.402	3.418	2.73
	Hollow glass	3.503	3.511	3.539	3.568	3.597	3.627	3.657	4.19
	Single glazing	3.828	3.885	3.942	4.000	4.058	4.241	4.300	10.97
South	Low-E hollow glass	3.059	3.045	3.031	3.000	3.006	2.995	2.984	−2.46
	Hollow glass	3.581	3.576	3.572	3.568	3.565	3.563	3.562	−0.56
	Single glazing	3.942	3.961	3.980	4.000	4.025	4.170	4.193	5.98

environmental performance through WWR changing is negligible, especially for south orientation. It can be concluded by the comparison of all cases that window type has a more significant effect on the building life cycle environmental impact than WWR, the life cycle environmental impact of building with low-E hollow glass window is about 25% less than building with single glazing window.

4. Conclusions and perspectives

The present study considers the building systems as a whole, involving material and building using aspects. When looking at the impacts due to building materials production and reusing, higher-reuse intensity implies a reduction in the absolute impact in all the impact categories when considering exterior window made of renewable resources such as glass and aluminium alloys.

This study demonstrates the life cycle environmental impact of buildings with different window type and WWR, research and development activities include: From the view of LCA, the WWR of typical office building can be larger than the upper limit of criterion. The WWR of single glazing window has the greatest influence on the life cycle environmental burden of whole building, especially for north side. But for the hollow glass window or low-E hollow glass window, the WWR has a little effect on the life cycle environment burden, for the low-E hollow glass window at south side; an increase of WWR could contribute to a decreasing in the impact of whole building life cycle.

Selecting a lower U-value window is more effective than WWR controlled for reducing the life cycle environmental impact in building designing process.

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